High-Power High-Gradient Testing of mm-Wave Standing-Wave Accelerating Structures

Emilio A. Nanni

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Acknowledgements

SLAC

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INFN-LNF

Bruno Spataro

Support by:

U.S. DEPARTMENT OF ENERGY

Office of Science

Outline

- Motivation
- mm-Wave Structure for High Gradient Tests
- Structure Prototyping and Fabrication
- Cold-Test Results for Accelerator Structure
- Conclusions

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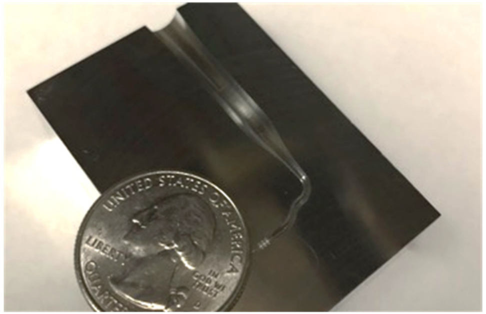
Next Generation Accelerators in Pursuit of Compactness, Efficiency and Performance

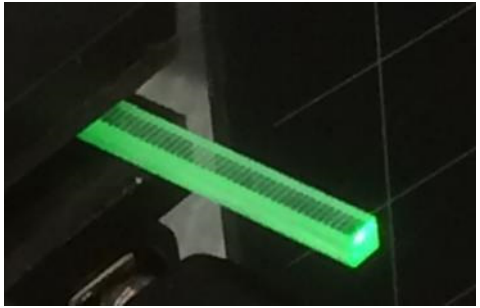
S-band Accelerators
30 MeV/m

mm-Wave/THz Accelerators
GeV/m



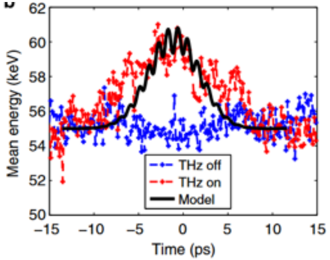
Klystron Source
10s MW, μs, ~3 GHz

mm-Wave/THz Sources
MW, ns, ~0.3 THz



Rapid Development of mm-Wave/THz Accelerator Technology

Acceleration



Nanni, E. A., et al. ***Nature Comm.*** **6 (2015): 8486.**

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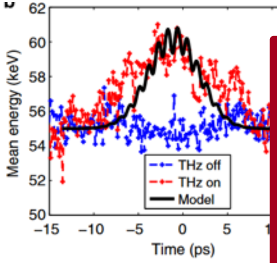
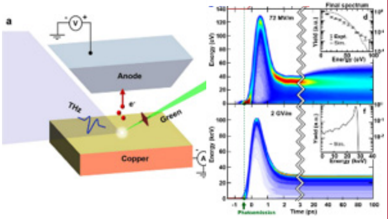


Nanni, E. A., et al. *Na*
Comm. 6 (2015): 848

Photoinjectors



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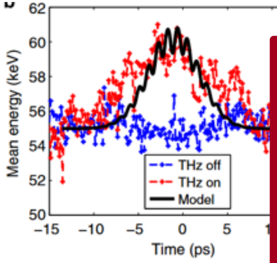

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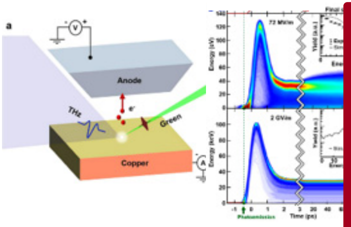

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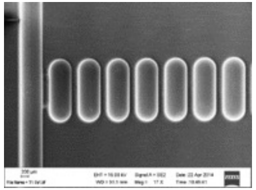
Beam-Driven GV/m Fields



M. Dal Forno, et al., *PRAB* 19.5 (2016): 051302.

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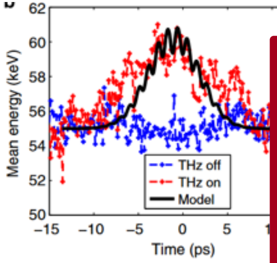

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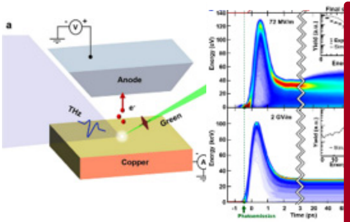

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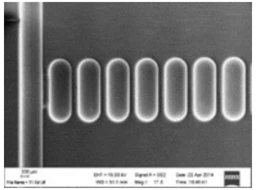

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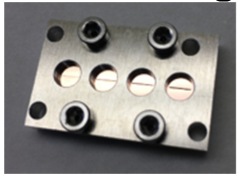
Deflectors and <1 fs Timing

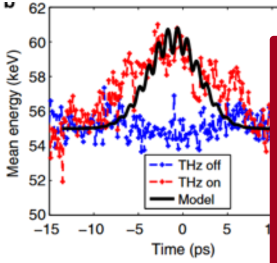


R.K. Li, et al., Ultrafast Optics
XI (2017) (2017)

Rapid Development of mm-Wave/THz Accelerator Technology

SLAC

Acceleration



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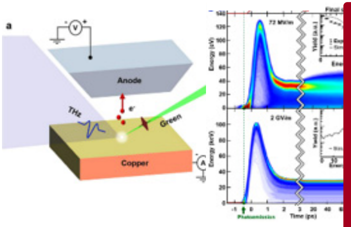

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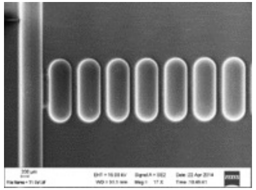

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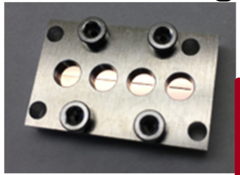

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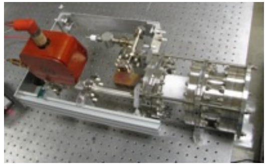
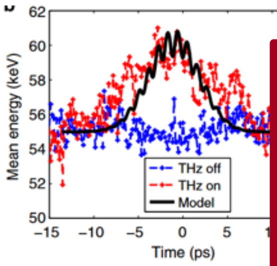
Toward Externally Driven GeV/m Accel.



Rapid Development of mm-Wave/THz Accelerator Technology

SLAC

Acceleration



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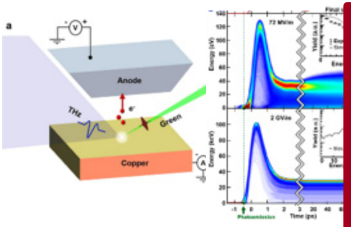

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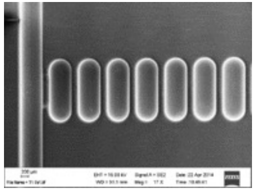

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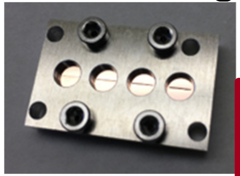

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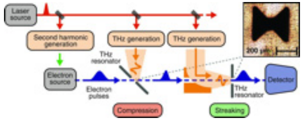
2017)

Growing International Community:

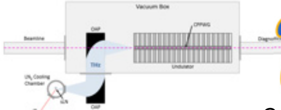
DESY MIT MPQ



Kealhofer, et al. *Science* 352.6284 (2016)

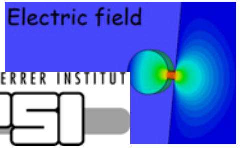
The Cockcroft Institute of Accelerator Science and Technology

Healy, et al., *UCMMT, 2017*



Ucla

Curry, et al.
arXiv:1708.06385 (2017).

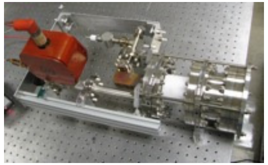


PAUL SCHERRER INSTITUT PSI

M. Dehler, HG2017

INFN SLAC

Toward Externally Driven GeV/m Accel.



Impacting Diverse Areas of Accelerator Technology:

- Precision Diagnostics and Beam Manipulation - <fs resolution
- Ultrafast Electron Diffraction - 100 fC, <10 fs
- X-ray Generation – few to 10s pC, low emittance
- High Current, High Luminosity >>10s pC, bunch trains

Higher Frequencies Can Achieve Higher Gradients

- Accelerating gradient is limited by breakdown (i.e. arcing or plasma formation)
- Breakdown threshold for surface electric field $E_s \propto f^{1/2}$
- Demonstrated operation with ~1 GV/m surface fields

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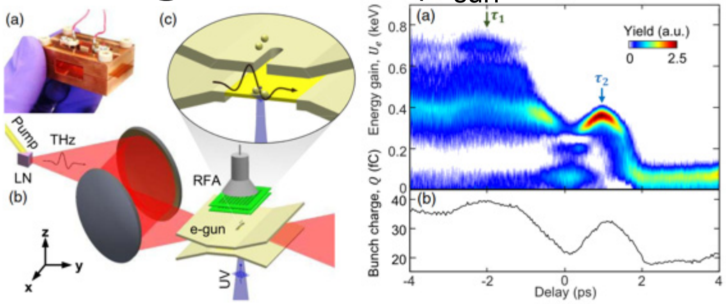
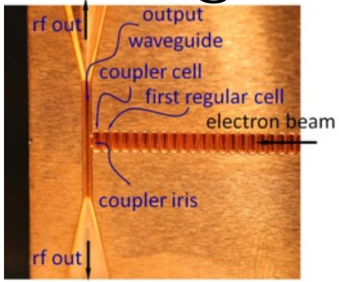
THz Guns @ MIT/DESY (E_{surf} ~ 300 MV/m)

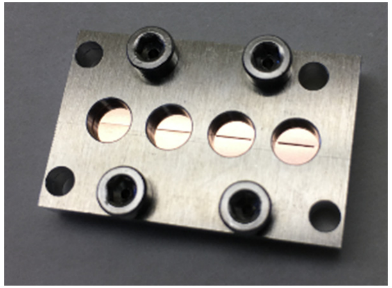


W. R. Huang, et al., Optica 3, 1209-1212 (2016).

Beam Driven @ FACET (E_{surf} ~ GV/m)



M. Dal Forno, et al., *PRAB* 19.5 (2016): 051302.



Streaking @ SLAC UED (E_{surf} ~ 150 MV/m)

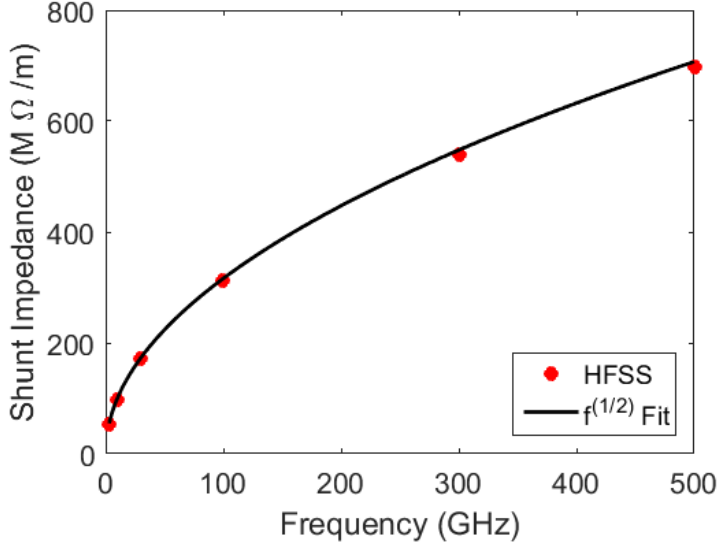
Other Examples:
Wimmer L. *et al.,* Nature Phys. 10, 432–436 (2014).
Nanni, E. A., et al. *Nature Comm.* 6 (2015): 8486.
Huang, W. R., et al., *Nature Scientific Reports* 5 (2015).

Advantages of Operating at THz Frequencies

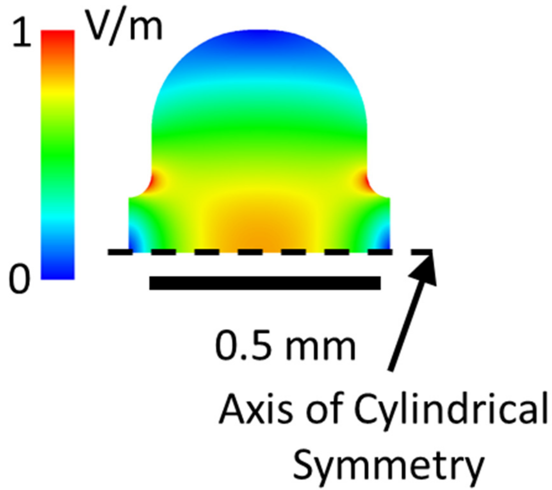
Additional advantages of high frequency structures:

- Shunt impedance increases as $f^{1/2}$
- RF pulse energy decreases as f^{-2}

Shunt Impedance for TM_{01} π-mode Structures



~300 GHz Structure



E. A. Nanni, et al., IPAC 2016
E. A. Nanni, et al., Journal of Physics Conf. Series. 874 (2017) 012039

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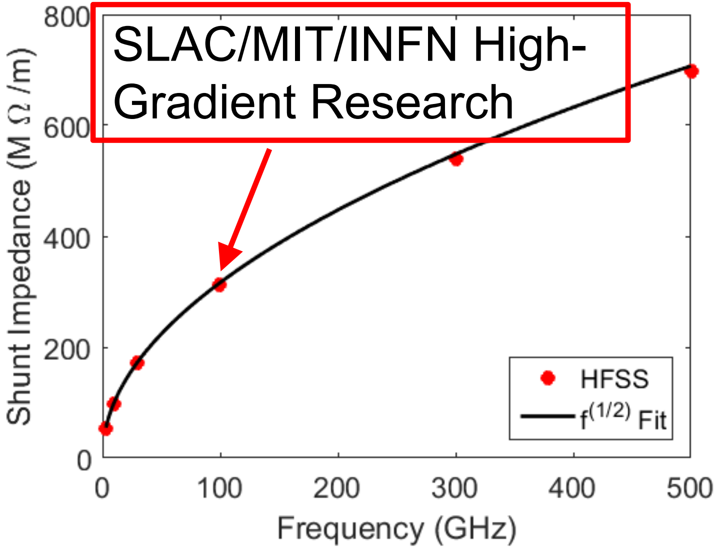

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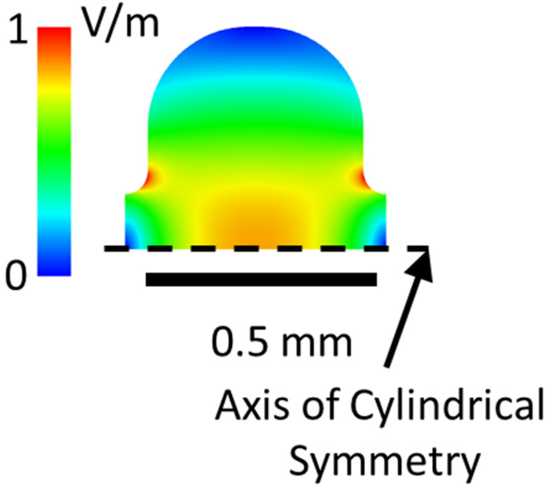

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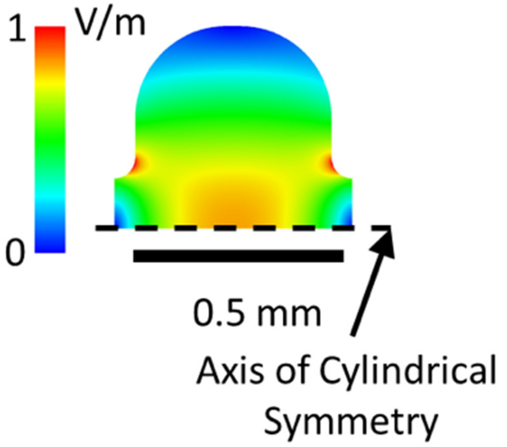
Comparison Between RF and THz Accelerators

- Scaling structure design from S-band to the THz range

Parameters for 100 MeV/m Gradient

Frequency	3 GHz	300 GHz
Stored Energy [mJ]	8450	0.013
Q-value [x1000]	17.96	2.05
Shunt Impedance [MOhm/m]	55	514
Max. Mag. Field [MA/m]	0.3	
Max. Electric Field [MV/m]	210	
Fill Time [ns]	2000	2
Loss in 1 meter [MW]	181	19



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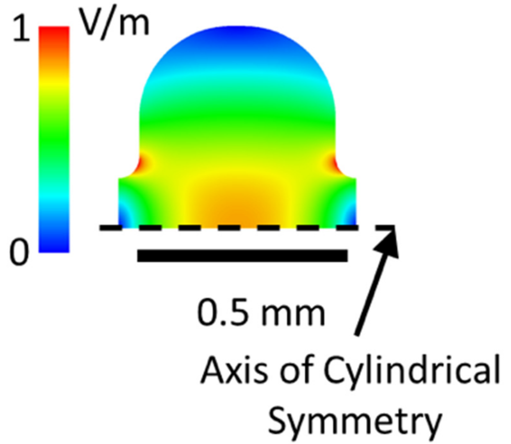


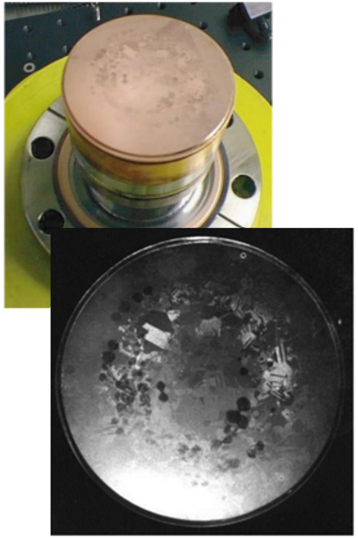
$P \times \tau$ decreases by 4 orders of magnitude
Potential to operate at 10s kHz vs 100s Hz

Pulsed Heating in High-Frequency Structures

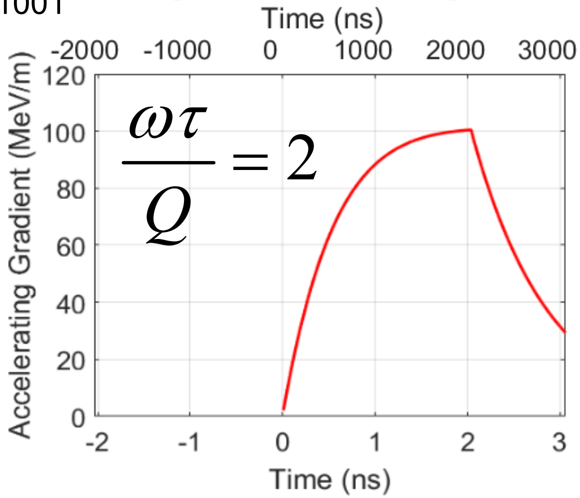
SLAC

- Surface temperature rise during RF pulse causes damage
- Surface resistivity increases as $f^{1/2}$
- Cavity fill time drops dramatically

Pritzkau, et al., Phys. Rev. STAB 2002
Laurent, et al. *PRSTAB* 14.4 (2011): 041001

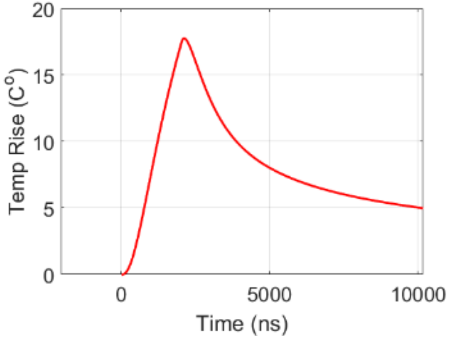


[3 GHz Structure]



[300 GHz Structure]

3 GHz Structure



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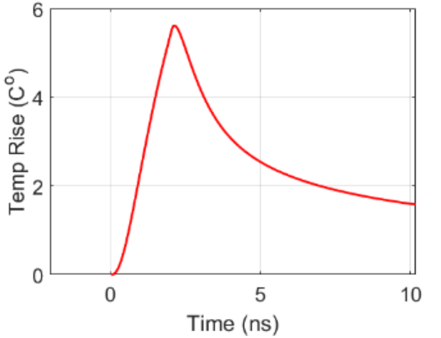

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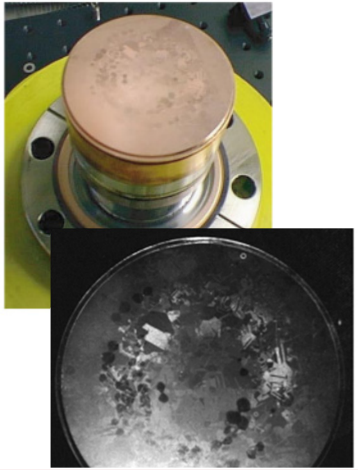

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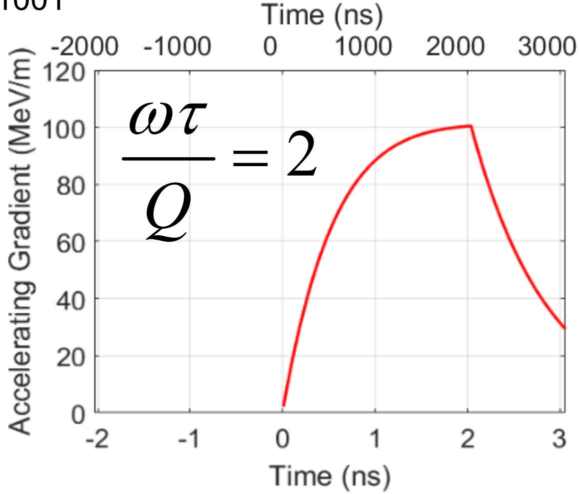

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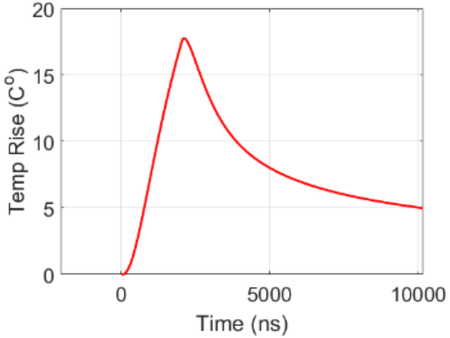
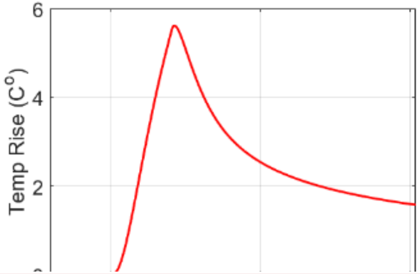


300 GHz Structure



Must Understand this New Regime for Frequency, Pulse Length, Stored Energy

Outline

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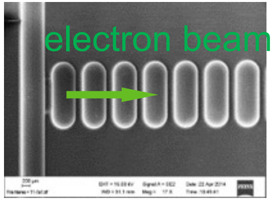
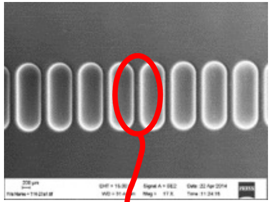
mm-Wave Metallic Accelerator Holds the Potential for High-Gradient Accelerators

- Increased shunt impedance and RF efficiency w/ mm-wave metallic accelerators
- Investigate geometry, gradient, pulse length and materials
- Achieved peak surface field of 1.5 GV/m
- Next step evaluate performance without drive beam

Observation of Damage:

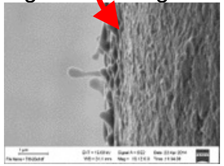


Input coupler, cells 1-7, no damage

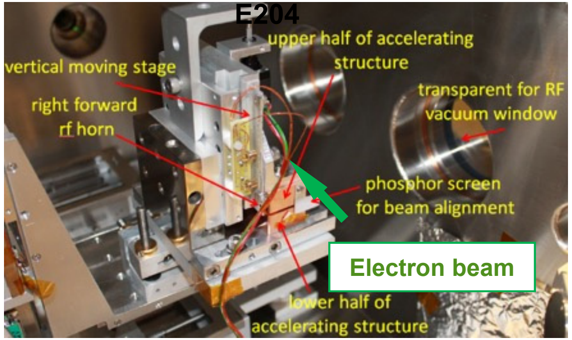


Cells 16-23, fist signs of damage

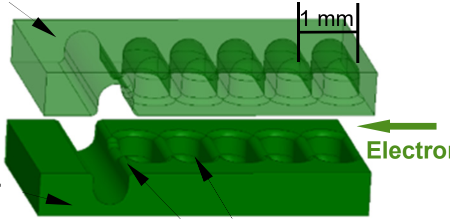
Acc. gradient 0.3 GV/m
E_{peak} 0.64 GV/m
Pulse Length ~2.3 ns



Experimental setup with copper accelerating structure – FACET E204



Solid model of the 100 GHz accelerating structure

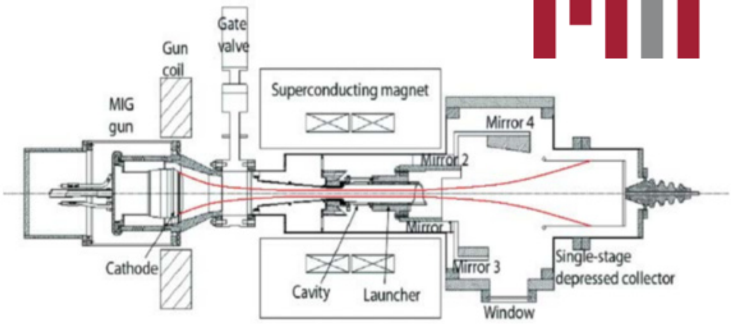


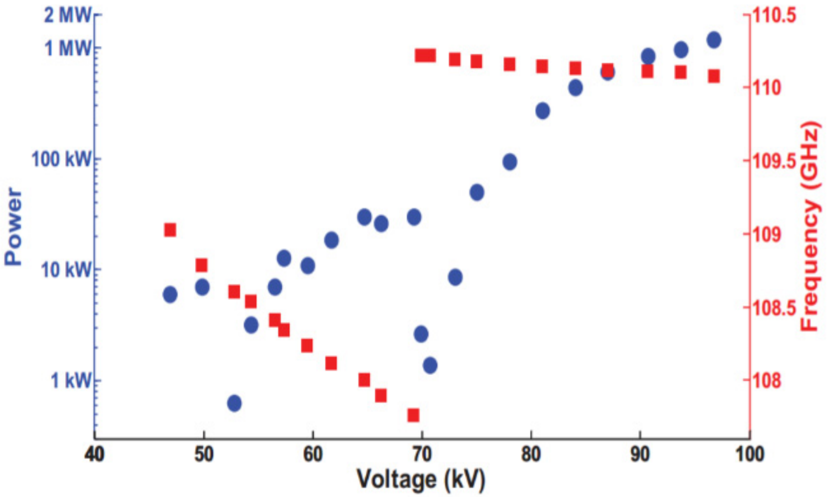
Dal Forno, Massimo, et al. *PRAB* 19.1 (2016): 011301.

MIT 1 MW Pulsed Gyrotron Oscillator at 110 GHz

- RF sources limited in mm-wave range
- MIT 1 MW gyrotron oscillator at 110 GHz with up to 3 μs pulses and frequency tunability

Tax, David S., et al. "Experimental study of the start-up scenario of a 1.5-MW, 110-GHz gyrotron." *IEEE Transactions on Plasma Science* 41.4 (2013): 862-871.





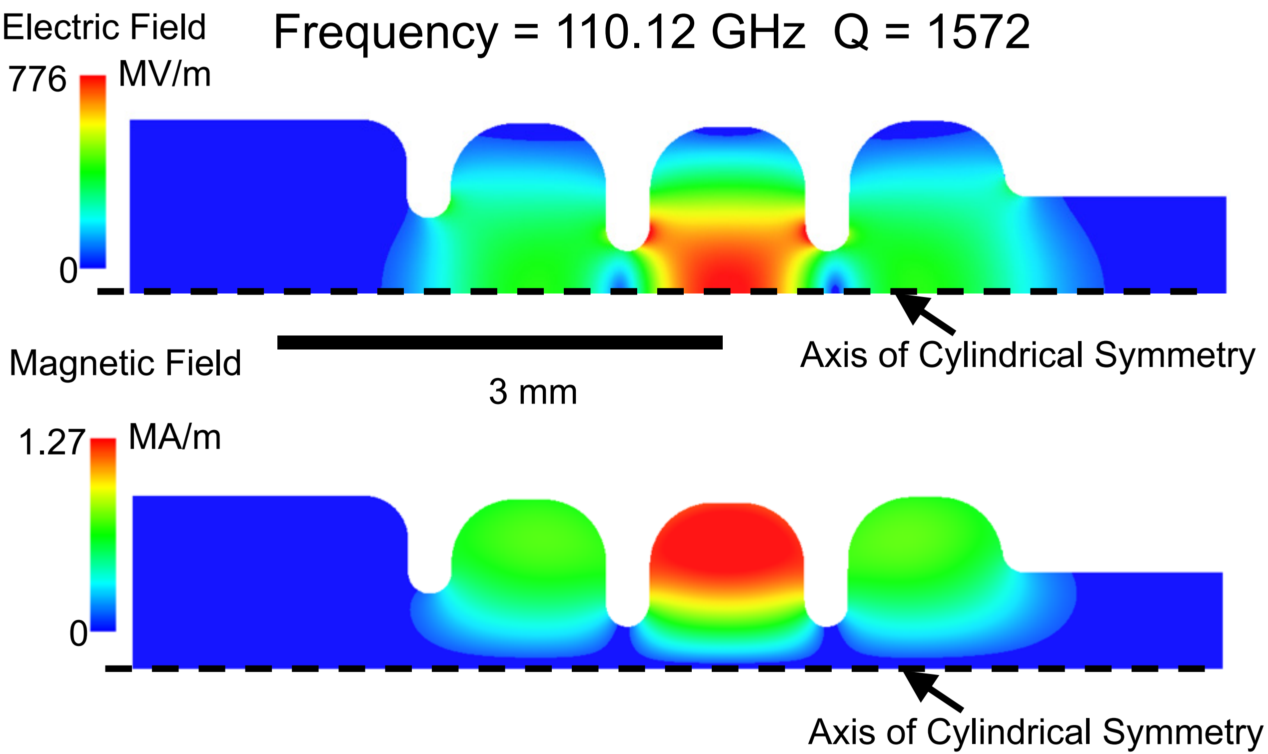
Field Distribution for a/λ = 0.105 and 1 MW of Dissipated Power – 400 MeV/m Effective Gradient

- Structure designed for comparison with X-band studies
- E_{max}/E_{acc} ~2.25

Iris Thickness (mm)

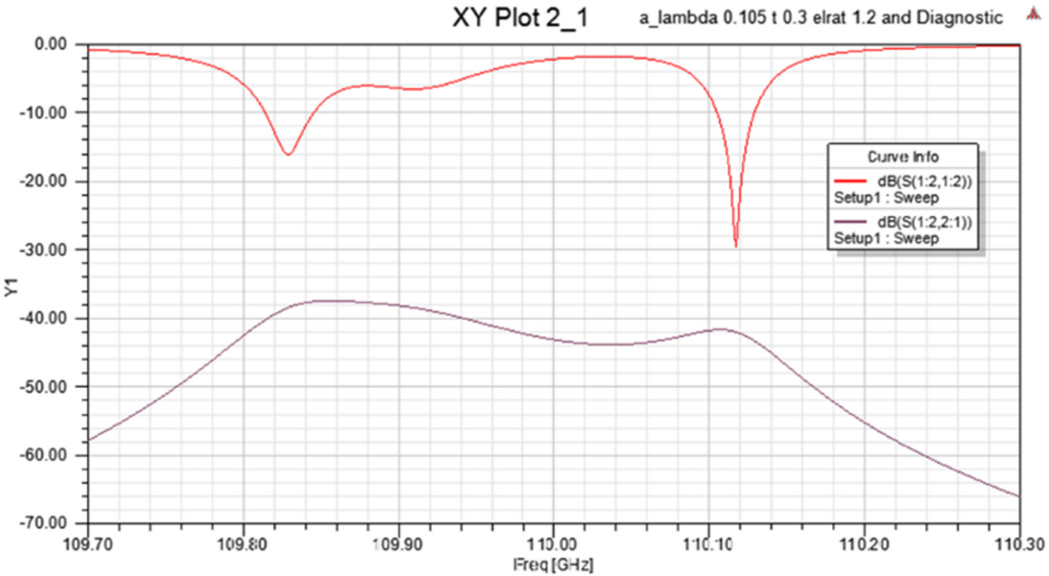
A0.286-T0.2-Cu

Iris Aperture Radius (mm)

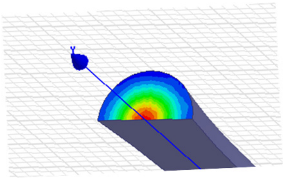


S-Parameters for ‘Single-Cell’ Structure for a/λ = 0.105 and 1 MW of Dissipated Power

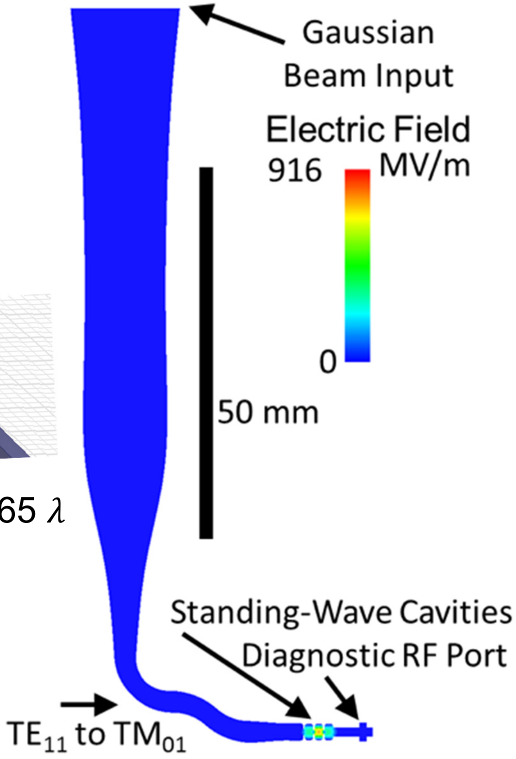
- Measure forward/reflected power through free space direction coupler and coupled power through diagnostic port



Field on horn aperture

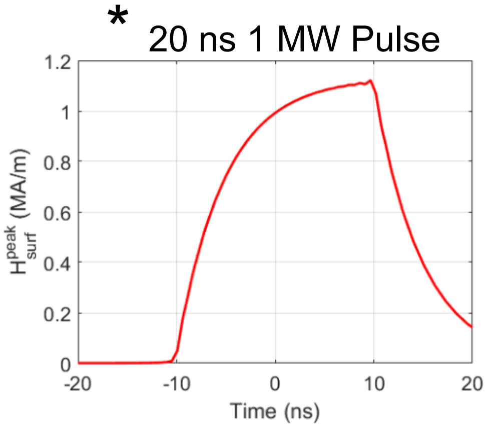


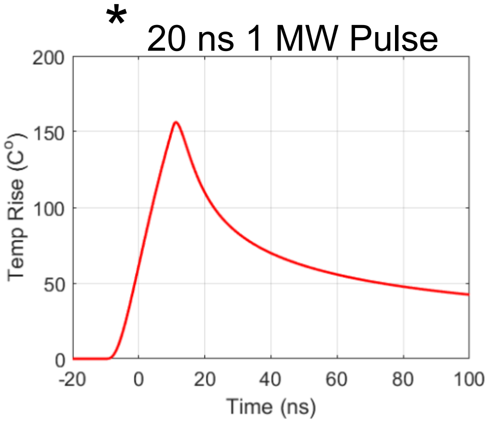
Beam waist 1.65 λ



Single Cell Parameters and Pulsed Heating

	A0.286-T0.2-Cu-110GHz
Dissipated Power [MW]	1
Peak Surface Electric Field [MV/m]	916
Peak Surface Magnetic Field [MA/m]	1.13
Effective Accelerating Gradient [MeV/m]	404
Accelerating Gradient in Central Cell [MeV/m]	419
Peak Surface Poynting Vector [W/μm²]	549
S/H² [Ohm]	430
Pulsed Heating (20 ns Input)* [°C]	156





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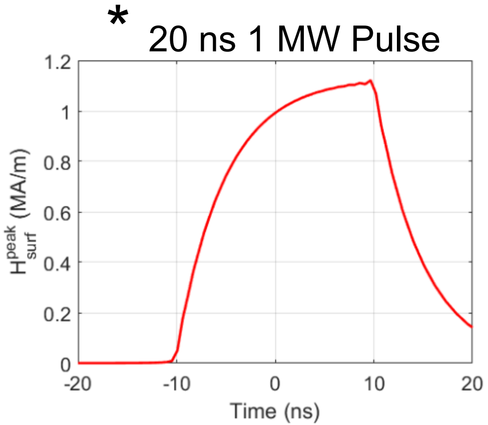
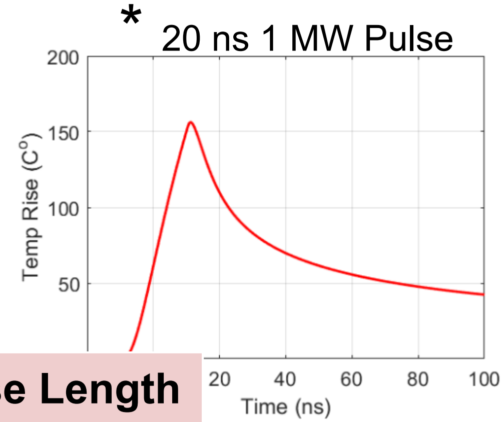




High Power Switch or Frequency Tuning to Select Pulse Length

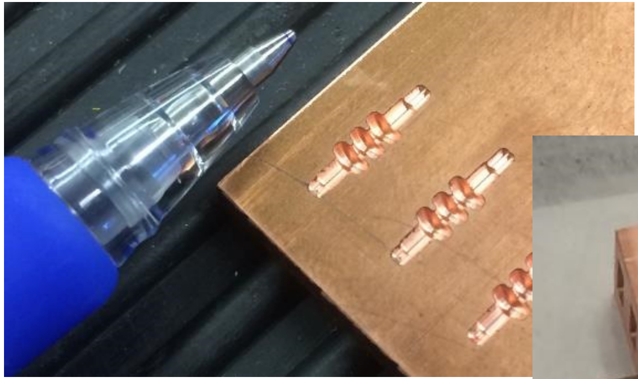
Outline

- Motivation
- mm-Wave Structure for High Gradient Tests
- Structure Prototyping and Fabrication
- Cold-Test Results for Accelerator Structure
- Conclusions

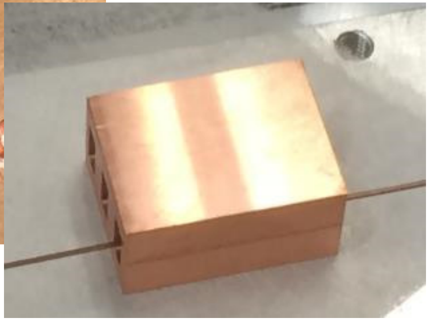
Prototyping of mm-Wave Structures

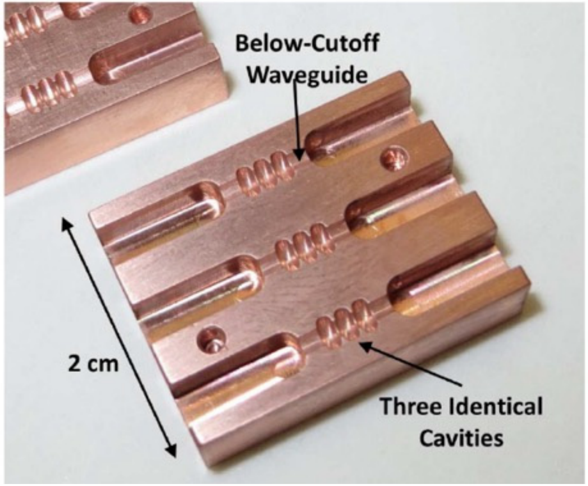
SLAC

- Assembly of structure and impact on RF and high gradient performance is a key concern
- Prototyping effort to test assembly using diffusion bonding and/or brazing
- Completed tests on 8 assemblies consisting of 22 separate RF structures
  - Focus is structural integrity, RF performance, frequency shifts



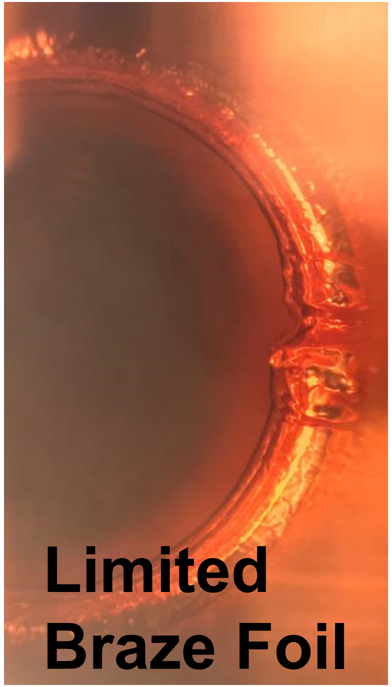
Coaxial Probes





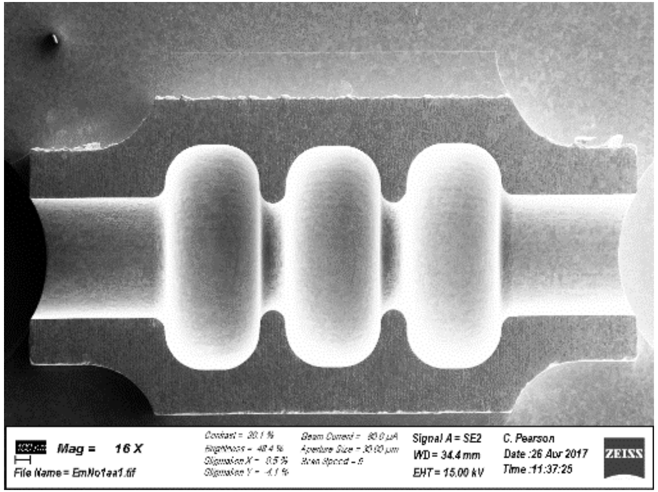
Comparison of Assembly Techniques

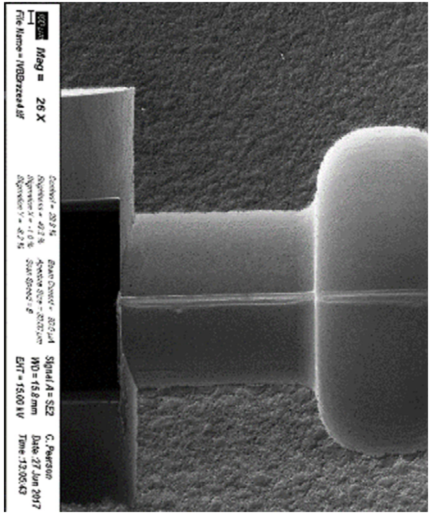
- Assembly from halves makes RF performance insensitive
- Local features significantly different

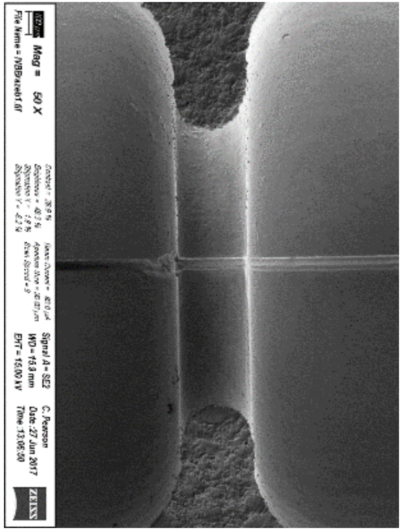


Details of Isolated + Limited Brazed Assembly

- New techniques and approaches needed for fabrication
- Successfully adapted split-cell approach to mm-Wave/THz range
- Braze foil tailored to cavity shape to control volume







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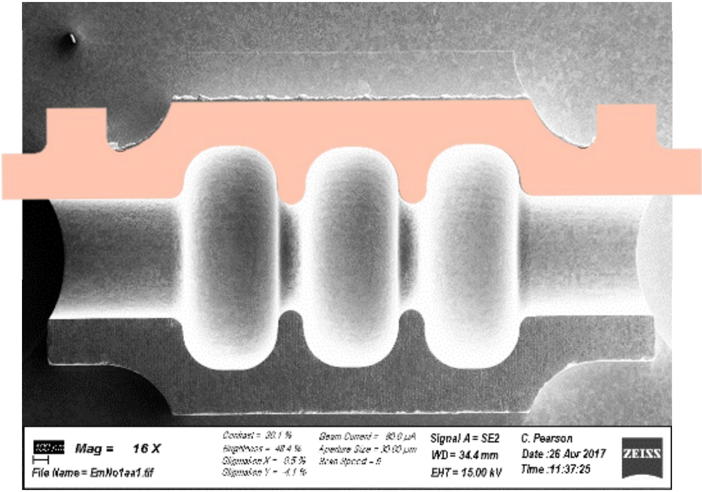
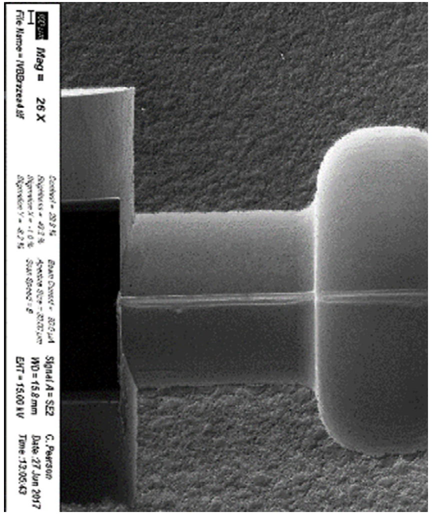
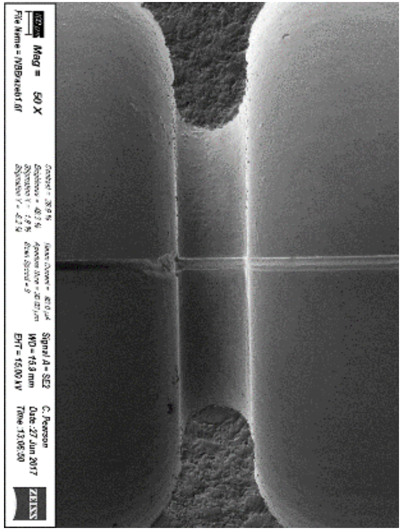


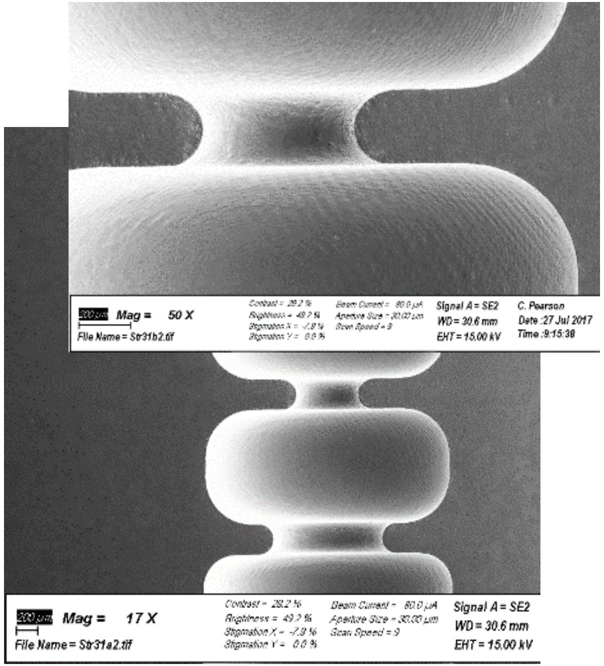




Structure Fabrication for High Gradient Test at 110 GHz

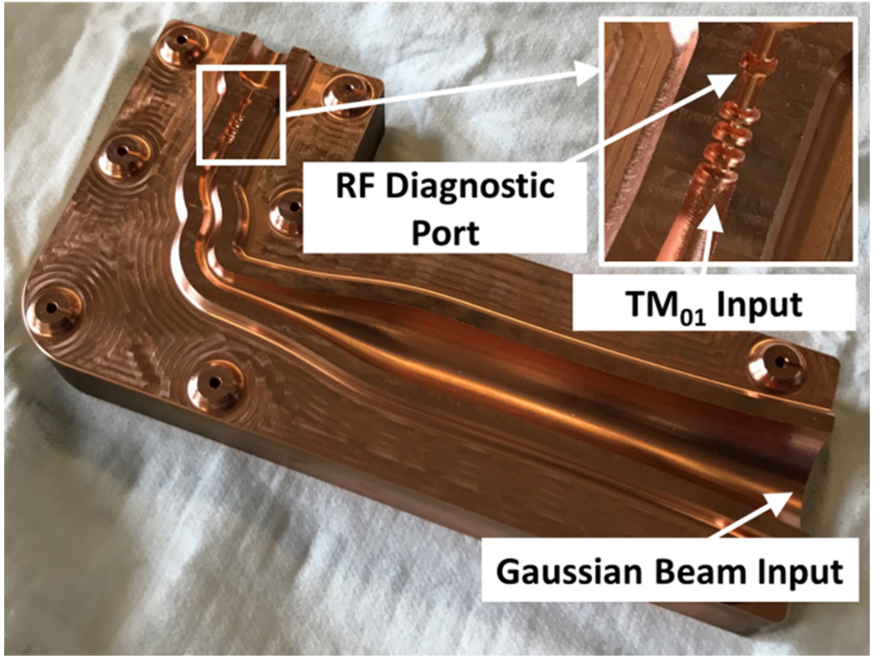
- First test with split-cell and diffusion bonding

Pre-Bonding SEM



Mode Converter and Cavities

a/λ=0.105



Applying Advanced Metrology for Close Loop Manufacturing

Outline

SLAC

- Motivation
- mm-Wave Structure for High Gradient Tests
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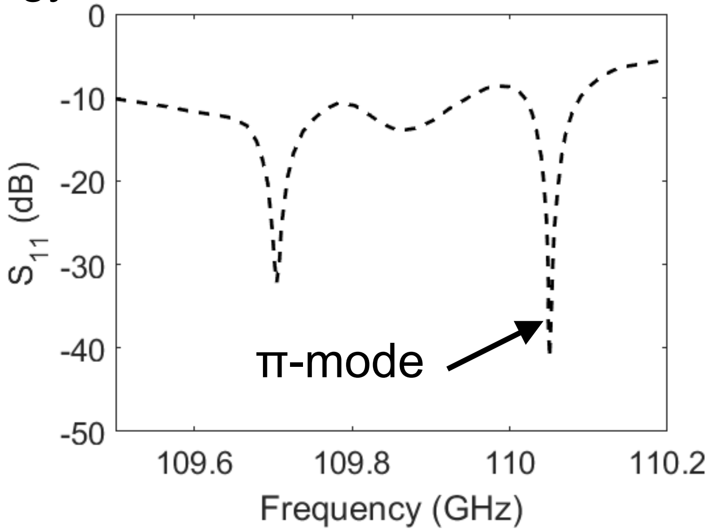
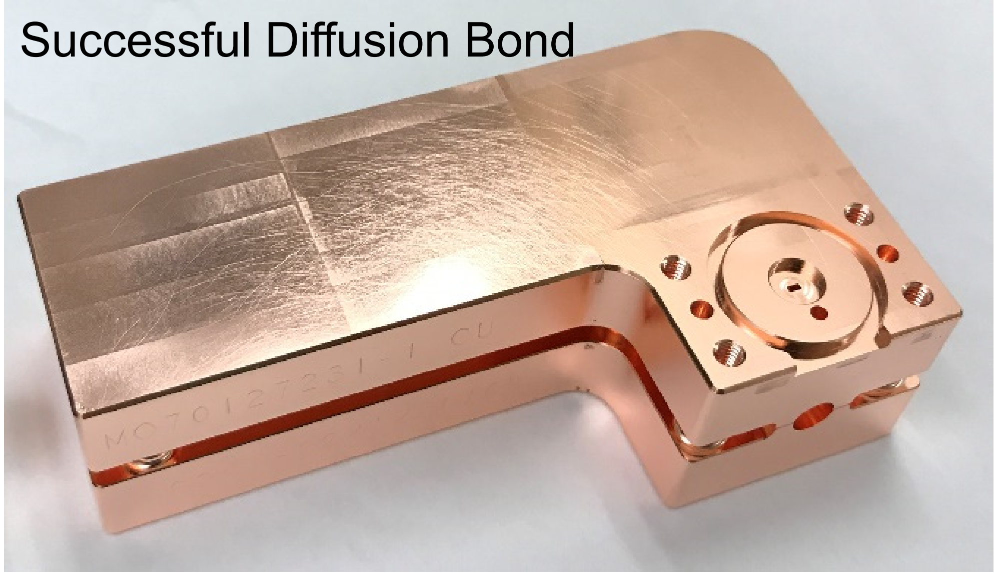
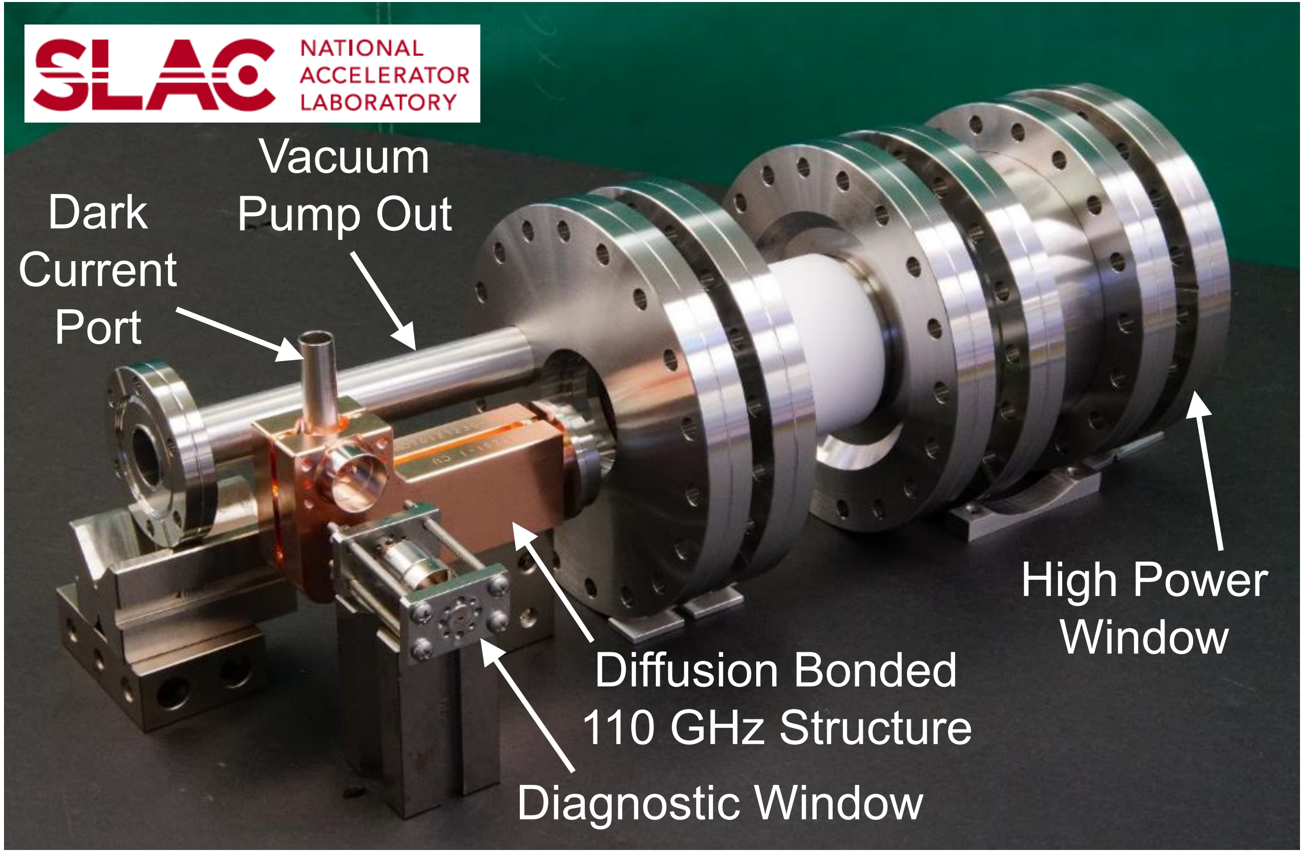
Cold-Test Results for of Diffusion Bonded Structure

- RF performance of cavities, mode converter, diagnostic port, high/low-power window complete
- Frequency within 0.01% of target @ 110.07GHz – thermal tuning to match MW gyrotron



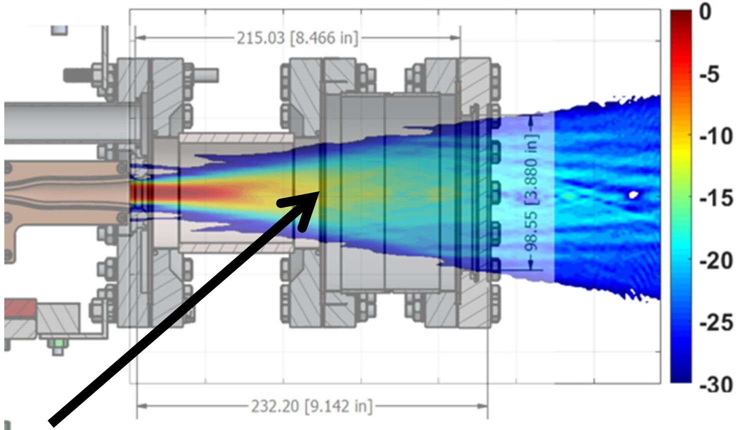


110 GHz High Gradient Structure Assembly Complete

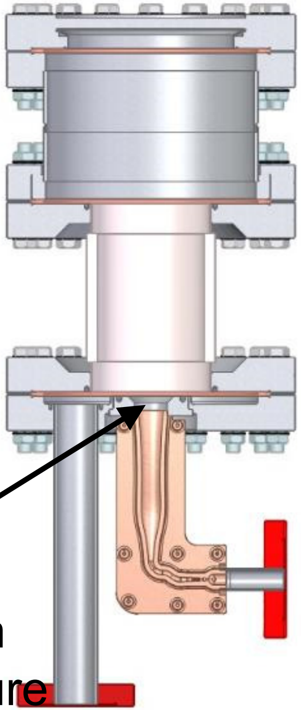


Efficient Excitation of THz Accelerating Structures

- Avoid lossy waveguides with quasi-optical transport and couplers



Measured/back-propagated field in the cut plane of the assembly



Free-space Gaussian beam coupled to structure

Schaub, Jawla

Nanni, Neilson, Jawla, Schaub

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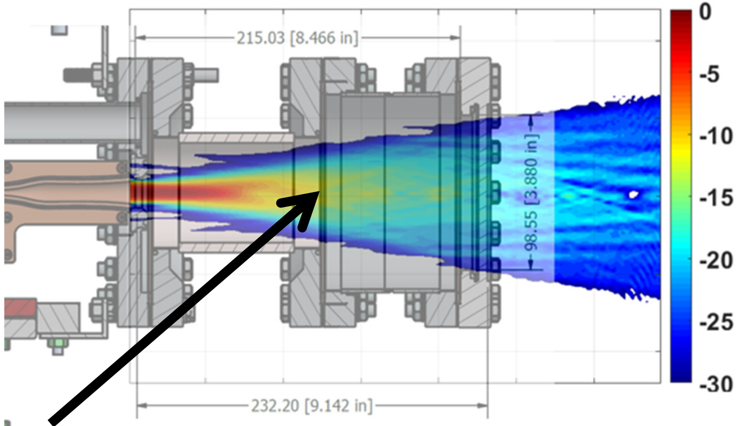
Schaub, Jawla



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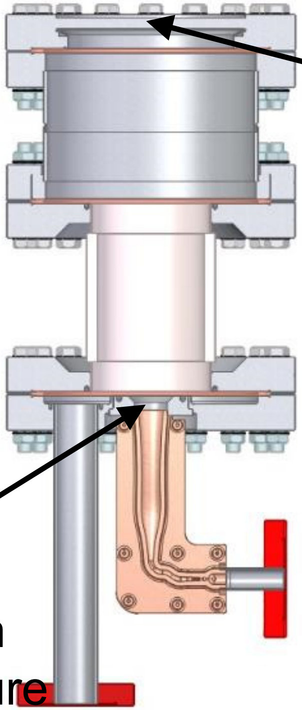
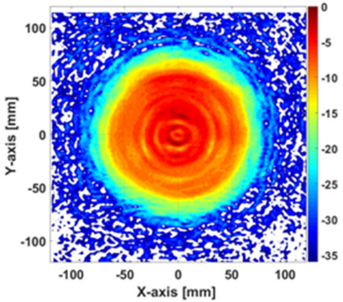
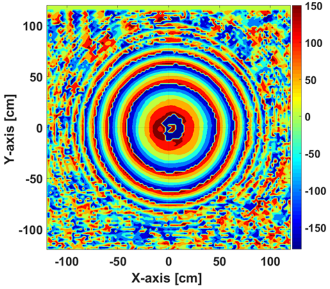


Free-space Gaussian beam coupled to structure

Measured Amplitude



Measured Phase

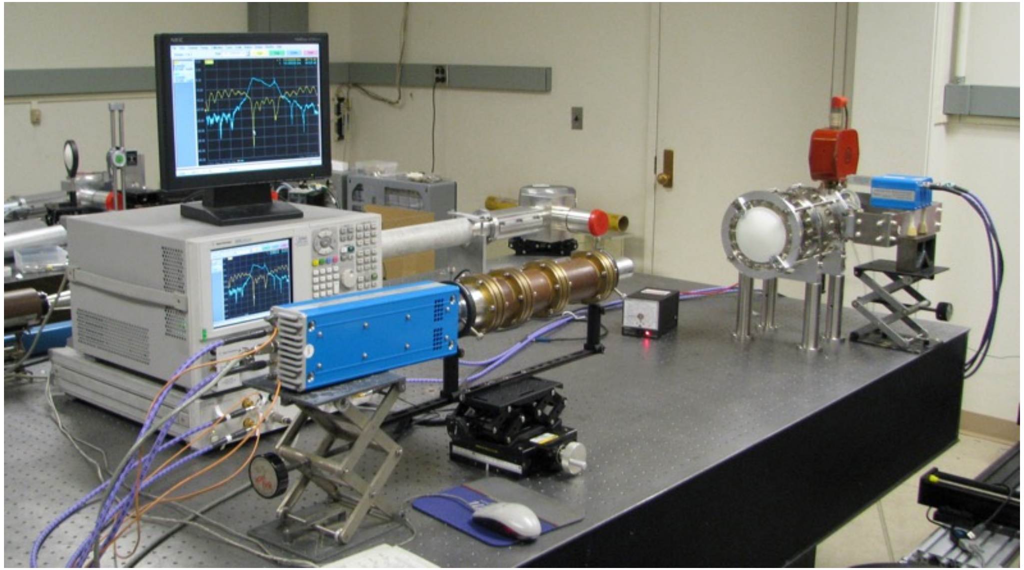


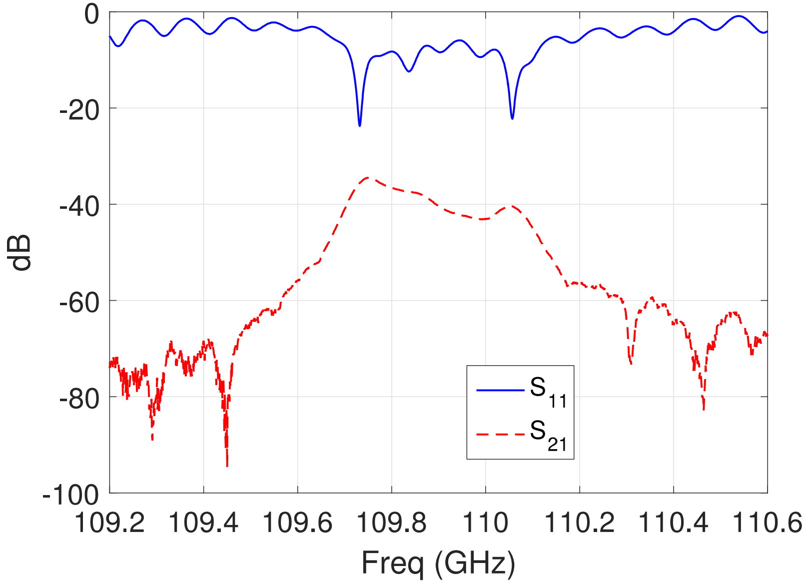
Versatile Topology Compatible with New Structures and Different Frequencies

Results from Quasi-Optical Transport Test

Schaub, Jawla

- Gaussian beam launcher used to test excitation
- Matches design - π-mode 110.1 GHz, S_{11}≈-25 dB, S_{21}≈-40 dB





Moving Forward to Test @ MIT, Target 1 MW Dissipated >400 MeV/m

Conclusions

SLAC

- mm-Wave/THz accelerating structures have shown the promise of high gradient achieving GV/m fields
- Understanding the performance of structures at high-frequency and high-field is needed for adoption
- Advanced manufacturing techniques deliver expected RF performance for mm-Wave/THz accelerating structures
- Quasi-optical coupling and transport demonstrated
- Integration with MW source now underway

Questions?